United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Note
INT-366



# Design and Construction of an Electric Arc Generator for Fuel Ignition Studies

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## ABSTRACT

*Describes design and construction of a system for creating a vertical, unbounded arc discharge in air. The arc is initiated by an exploding tungsten wire and is turned on and off by a silicon-controlled rectifier switching system. As a safety precaution, all circuits are computer controlled through fiber optic and pneumatic connecting links. The SCR switch and decommutator switch are fully protected against excessive current and voltage rate-of-rise. Typical waveforms for short-circuit and arc switching are presented.*


KEYWORDS: arc generator, arc discharge, vertical arc

Lightning flashes to ground consist usually of a discharge with a peak current flow on the order of 30,000 amperes. The discharge duration is about 400 microseconds. Occasionally, a weaker spark discharge of 10,000 amperes or so will be followed by a much smaller current flow. This 20 to 500 ampere current lasts up to 500 ms, and is called a continuing current by lightning researchers (see Uman 1984 for summary). The continuing current is responsible for 95 percent of all lightning-caused wildfires (Fuquay and others 1972).

Because this fire-starting mechanism is of such importance, and because means are now at hand to locate the ground termini of lightning discharges (for example, the Bureau of Land Management's IAMS system), we have been working on a means of predicting the probabilities of fire starts by lightning discharges (Fuquay and others 1979). The probabilities, together with accurate lightning locations in a predictive system, will enable cost savings in fire-spotting patrols and aid in control/confine/contain decisions (Latham 1979).

To predict the probability of fire occurrence, we need to determine only the probability of ignition of a fuel complex; the propagation probability of the fire is known (Wilson 1985). Ignition probability depends on the physical parameters of the fuel, such as fuel type, bulk density, and the like; on fuel state, in particular moisture content; and on the reaction of the fuel to the passage of an electrical arc discharge.

We began our study of this problem by using modeling techniques to obtain some sense of the characteristics of the continuing current arc channel (Latham 1980, 1986). Combining these with known characteristics of the continuing current, we formed a set of criteria for an electric arc to simulate the continuing current in the laboratory. Using these criteria, we designed and constructed equipment to generate the arc and measure its current flow.

## DESIGN CRITERIA

From measurements of naturally occurring continuing currents and from our modeling efforts, we obtained a set of desired characteristics for the arc discharge:

- current in the arc from 20 to 500 amperes dc
- arc duration 20 to 500 ms (0.02 to 0.5 sec)
- fast start and stop of current flow
- core temperature 6,000-8,000 K
- length greater than 10 cm
- diameter 1-6 cm

In addition to these modeling criteria, safety of personnel and building was of paramount importance in switching and power supply design.

We needed an estimate of the voltage requirements of the power supply. We could expect an electrode drop of 25 to 30 volts across the anode and a like drop at the cathode (Cobine 1958). Model (Latham 1980, 1986) and experiment (King 1961) showed that a 10-cm-long arc would have a voltage drop of about 100 volts, nearly independent of current flow, over our range of interest. Although we wanted a constant current source, we could not find a dc control element that would serve. The current

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flow could, however, be set by a series resistor. The series resistor would also act as a current-limiting element to prevent total "meltdown" in the event of circuit failure. The source voltage necessary for a 10-cm arc from a simple equivalent circuit (the power supply in series with the limiting resistor and the arc) was calculated as:

$$Vs = 700 * R_{sm} + 0 \quad \text{(arc shorted)}$$
$$Vs = 500 * R_{sm} + 150 \quad \text{(10-cm arc)}$$

where Vs is the source voltage, $R_{sm}$ is the minimum source series resistance, the maximum current flow is 700 amperes, and the arc voltage drop is 150 volts at a current of 500 amperes. The maximum current flow was chosen only slightly higher than the cranking current of the (anticipated) battery supply. Under these conditions, the source voltage is 525 volts, the minimum series resistance 0.75 ohms, and the maximum series resistance (corresponding to 20 amperes of current) is 18.75 ohms.

The source voltage and short-circuit current established the minimum values for the capabilities of the switch. It must control a sustained current of at least 700 amps and have a voltage breakdown of at least 525 volts. We used an engineering safety factor of about 2, requiring 1,000 volts standoff and 1,500-2,000 ampere current capacity for 1 sec as the design values for the switch. At this current, for 1 sec, the series resistor must dissipate 1,500 to 2,000 kw without heating to destruction. Because we expected an interval of several minutes between arcs, "one-shot," or nonrepetitive, ratings of switching devices were used.

## SAFETY

A primary consideration in the design and construction of the arc system was personnel and building safety. We needed a high-voltage supply capable of up to 1 kiloampere current capacity at a voltage in excess of 500 volts; therefore, a means of preventing access to and interlocking the supply was mandatory. Because of the high current needs, and the state of the building electrical supply, we could not use transformer-rectifier combinations for the primary supply. After some alternatives had been considered, we decided that forty large automotive storage batteries connected in series would serve. These would be placed in a building separate from the main building, and the separate building kept locked at all times. Although lead-acid batteries only generate hydrogen when being charged rapidly, personnel fears about formation of hydrogen gas were allayed by using the ventilated outbuilding, and by using small, inexpensive automotive battery chargers. To allow this use, and to prevent danger from a permanent series connection, switches were designed for automated series connection of groups of four permanently series-connected batteries. All 10 of these switches were to be closed only just prior to generating the arc. Further safety considerations prompted the choice of a combination of pneumatic and fiber optic devices to do all control functions. No connections of any kind would be made to commercial power lines; additional storage batteries would supply all needed voltages in the switching circuit. An easy-to-use manual switch would interrupt the high-voltage circuit in extremis. This switch would also disable all other circuits in the high-voltage switching circuit.

After much deliberation, we decided that the high-voltage circuit would have no earth ground. If "one hand for the work and one for me" was obeyed, personnel could not inadvertently bridge the power supply. All circuitry for the high-voltage switch would be completely enclosed in cabinets and attention paid to security of all electrical insulation.

Further safety precautions included provision of ample numbers of fire extinguishers of the proper kind, a vent with fan for removing smoke and vapors, first aid kits, appropriate operator training, and great numbers of high voltage signs. Because we planned to use tungsten for the exploding wire, toxicity of tungsten and tungsten oxide was checked and found nil.

## ARC GENERATOR CIRCUIT DESCRIPTION

The arc generator as it now exists is best understood by examining the figures (schematic diagrams and photographs) depicting its components. Begin with figure 1, the overall block diagram. Arrows point to control and power connections. The main elements of the generator are: (1) the computer and fiber optics interface, (2) the controller electronics, (3) the high voltage power supply with its series switches, (4) the arc-switching circuit, (5) the electrode assembly (arc carrier), and (6) the current measurement instrumentation.

The PET 4001 computer[2] is a now obsolete microcomputer with 32k bytes of RAM and BASIC in ROM. We chose this computer because it was on hand and because it has an IEEE488 bus driver built in. It has more than sufficient memory to do the job, a dual floppy disk drive storage, and a printer. The computer controls, through its IEEE bus, a binary interface that drives and receives information from the fiber optics interface to the controller (fig. 2). The bus also connects the computer and the storage oscilloscope. The fiber optics interface is an array of drivers and receivers (fig. 3A,B). All system functions are controlled by this computer, including arc duration, system sequencing, operator instructions, and operation of the sampling oscilloscope. An external fiber optic pushbutton is used to fire the arc switch. Figure 2 is a photograph of the computer, fiber optics interface, and sampling oscilloscope assemblies.

The pneumatic supply referenced in figure 1 is relatively simple. Air from the laboratory supply at 70 psi is passed through a dryer, regulator, and buffer tank. The regulator was set at 55 psi. A valve was installed on the fiber optics interface panel to control the air supply to the rest of the apparatus. This valve, as a safety feature, is not automated, so the operator can shut down the pneumatics at any time.

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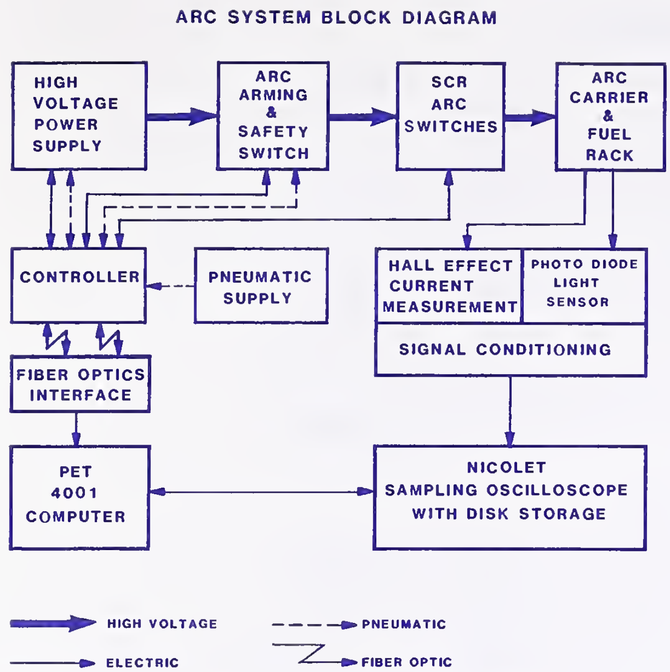



Figure 1—Arc generator system block diagram.

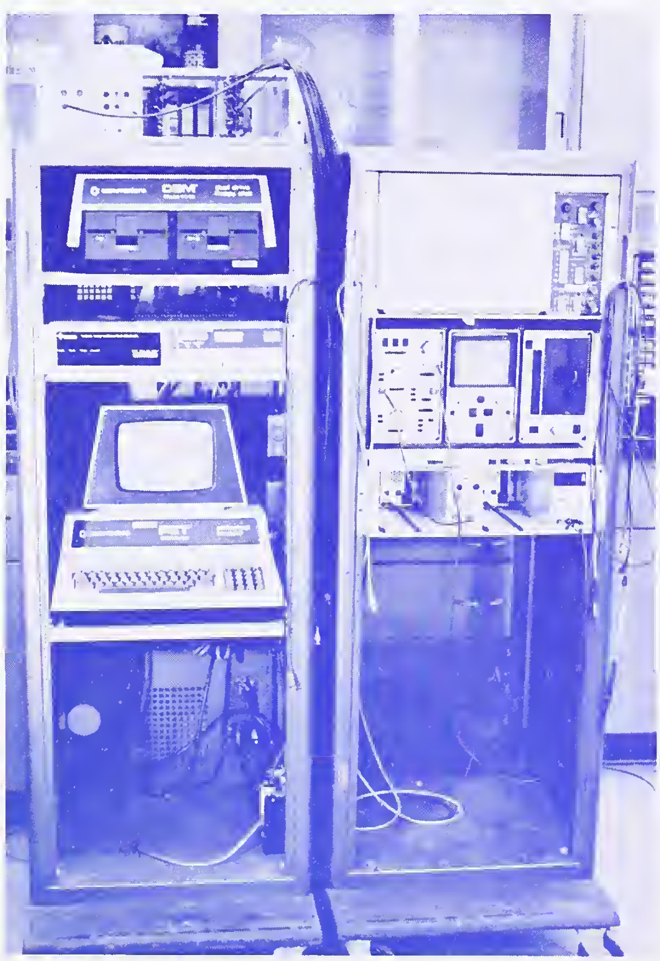
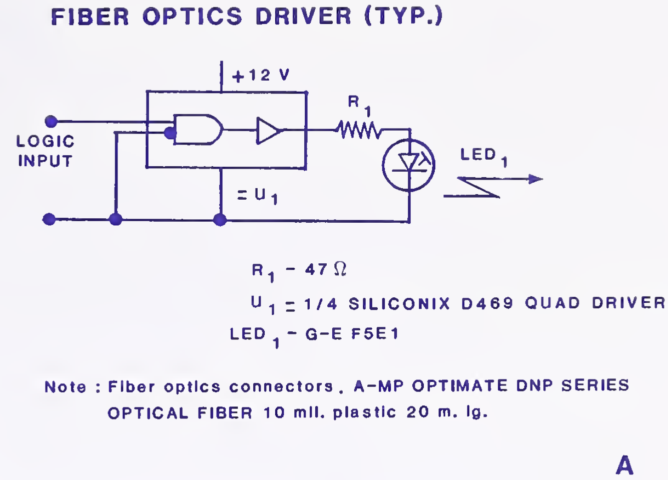


Figure 2—The computer and fiber optics interface (left) and the Hall-effect current measuring signal conditioner and digital sampling oscilloscope (right).



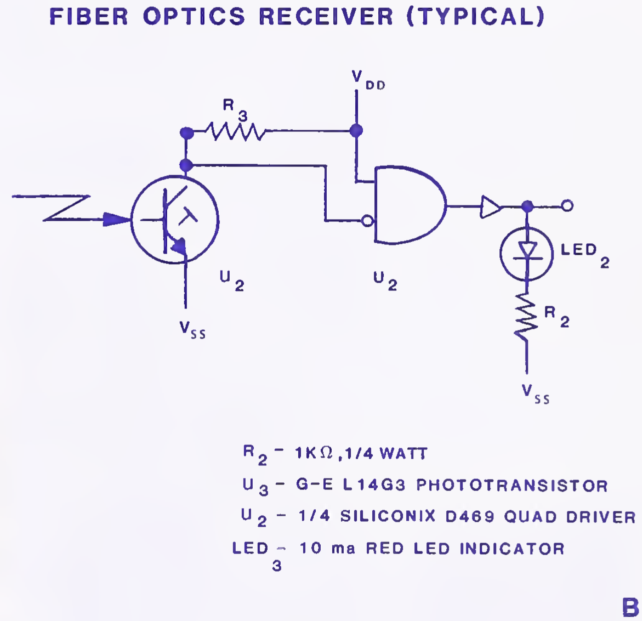




Figure 3—Fiber optics driver (A) and receiver (B) circuit diagrams.

The controller (fig. 4) is connected to the non-high-voltage world through fiber optics and the pneumatic supply line to meet the safety criteria given above. It resides, along with its 12-volt battery power supply, in the arc switch cabinet. The arc arming switch and the high-voltage switch assembly are pneumatically driven, the pneumatics controlled by fiber optics valve driver circuits (fig. 5). Pneumatic cylinders have long mechanical throw with excellent force, allowing for switches with large air gap electrical isolation. The safety bleed valve is part of the manual safety switch (which we will see later) and is opened when that switch is in the open position. If this valve is open, the air supply to the high-voltage circuits is removed, disabling the high-voltage power supply and the arc arming switch.

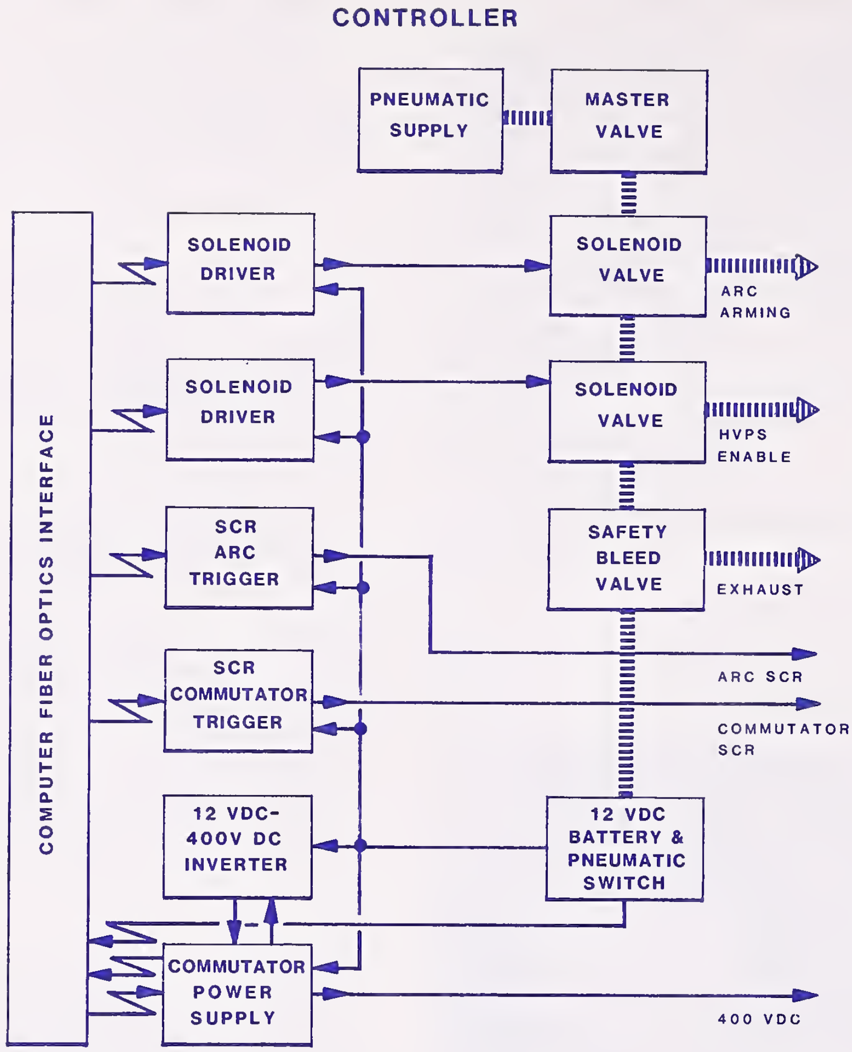



Figure 4—Controller block diagram (ref. fig. 1).

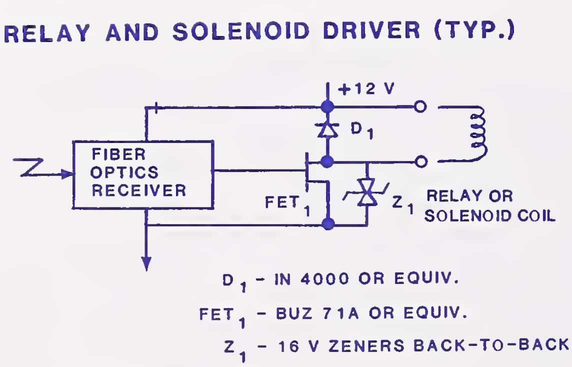
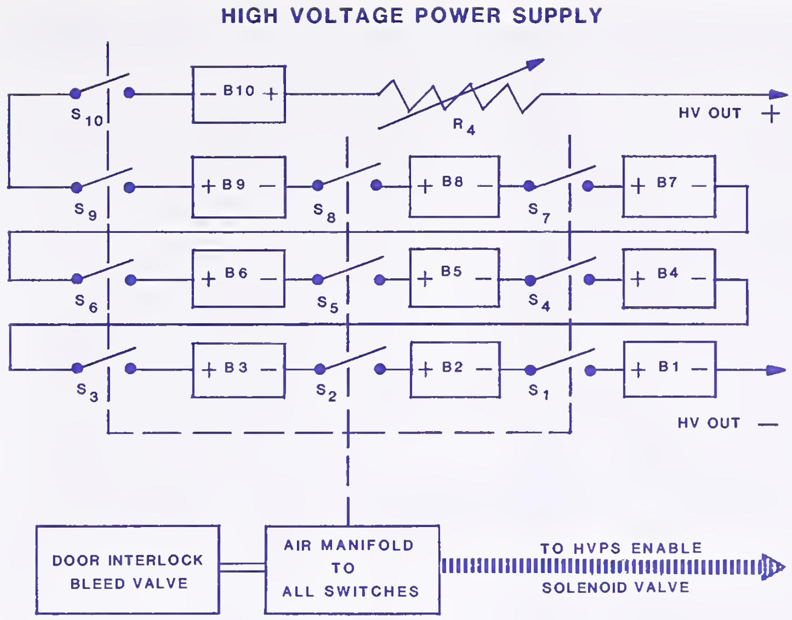



Figure 5—Relay and solenoid driver (ref. fig. 4).

The high-voltage power supply, figure 6, consists of forty 12-volt heavy-duty automotive batteries ($B_1$-$B_{10}$), each having a cranking current of 620 amperes. The cranking current is the current source value at zero degrees Fahrenheit. The current source value is higher at the 50 °F minimum temperature of the battery shed. The batteries are permanently connected in series groups of four, and 10 pneumatic switches ($S_1$-$S_{10}$), shown in detail in figures 7 and 8, connect the four-battery groups together in series immediately before an arc discharge is to be made. These switches, as can be seen in figures 8 and 9, are built on the lumber used for shelf supports. Figure 8 is a detail photograph of a switch, and figure 9 shows the switches with protective covers in place. The little indicator flag evident in figure 8 is displayed above the safety cover when the switch is closed. A valve is connected to the building door so that if the door is opened when the series switch circuit is energized, the air supply is interrupted, and all switches in the battery building open.




$B_1$ - $B_{10}$ - CLUSTER OF FOUR 12 V LEAD-ACID BATTERIES, 620 A CRANKING CURRENT, GENERAL BATTERY CORP. 31-620

$R_4$ - 0-10 Ω RHEOSTAT. 50 EA. 4.8 MM DIA. x 61 CM LG. CARBON WELDING RODS IN SERIES

$S_1$ - $S_{10}$ - PNEUMATIC HIGH VOLTAGE SWITCH (See detail)

Figure 6—Circuit diagram of the high-voltage power supply (ref. fig. 1).

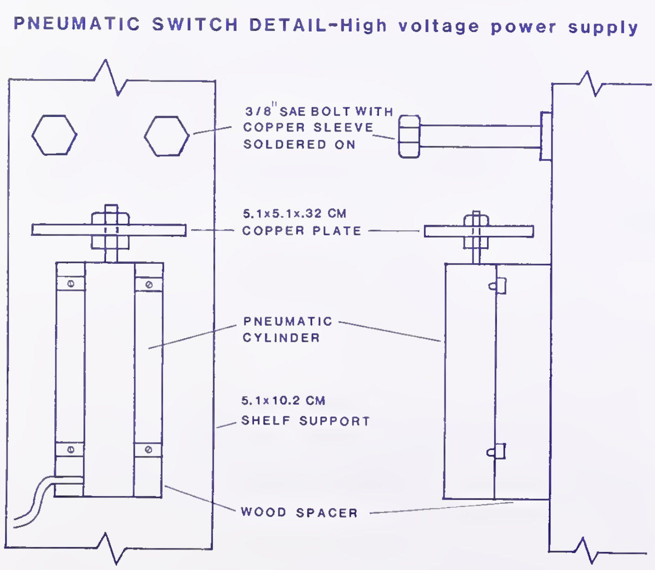



Figure 7—Detail drawing of the high-voltage power supply switch (ref. fig. 6).

Figure 8—One of 10 high-voltage switches (ref. fig. 7).

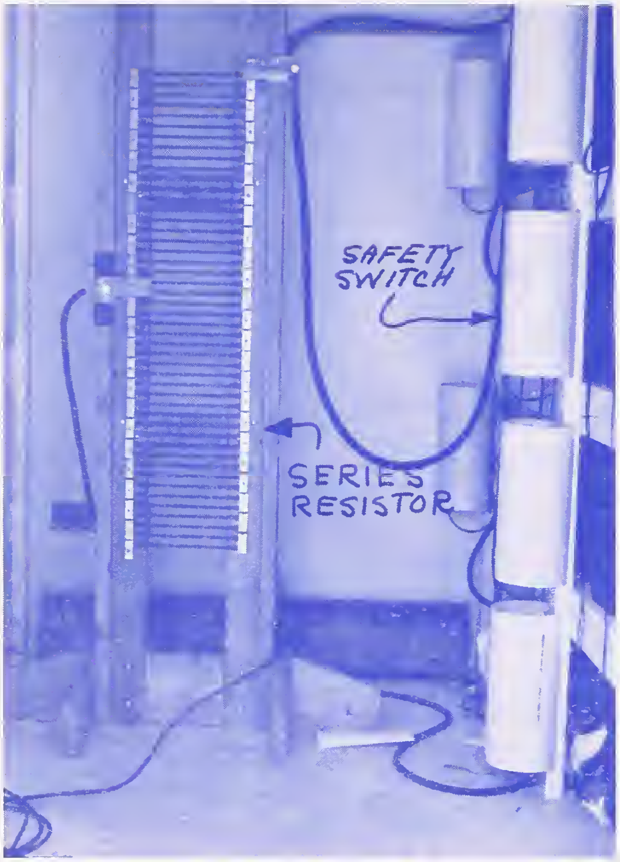


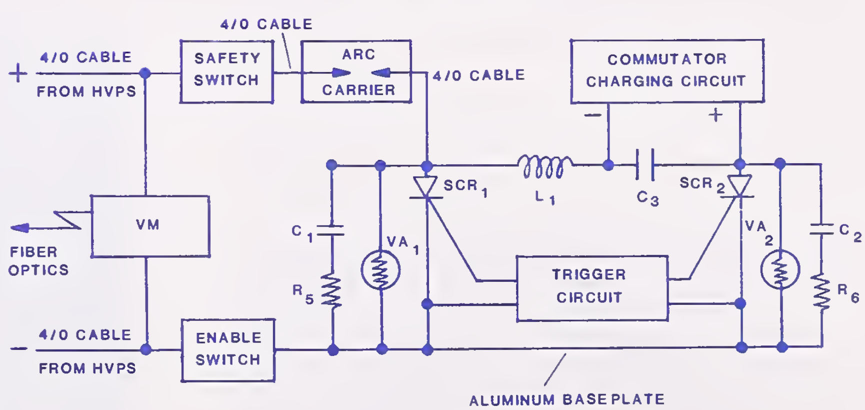

Figure 9—Part of the battery building interior. The series resistor carbon rod array is on the left. The movable tap is on the left side of the resistor array. The safety switches are covered for safety, and the use of the flag in the photograph of figure 8 is apparent.

The series current-setting resistor ($R_4$, fig. 6, and shown in the photograph of fig. 9 on the left side) is composed of 50 welding rods clamped by brass clamps in a series arrangement. The rod size was calculated by simultaneously considering the resistance of an individual rod, the temperature rise of the rod during a maximum current experiment, and the consequent thermally caused expansion of the rod. The resistance of commercially available arc welder cutting rod was juggled against an allowed thermal expansion of 0.1 mm for the rod. The result is the array of fifty 4.7-mm diameter rods each 61 cm long. There has been no breakage due to thermal stress (although we find that the rods do not bend readily). The clamps are not rigidly fastened to the frame on which the resistor is constructed.

The arc switch and its accompanying circuitry are shown in figures 10 and 11. An attempt to use a physical switch quickly convinced us that, although silicon controlled rectifiers (SCR's) with the needed reverse voltage and peak current capability were expensive, they would provide the fast and easily controlled switching that we needed. An SCR with a turn-on time on the order of 1 microsecond, turn-off on the order of 30 microseconds would meet our needs. The National NL-C458 1,400-volt, 2,000-amp fast-switching device was selected.

SCR's must be protected against electrical environment excesses: current rate of change (di/dt), rate of voltage application across the device (dv/dt), excess voltage across the device, and excessive current (Gutzwiller 1961;

**SCR ARC SWITCH**




$R_5$, $R_6$ - 20Ω/2 W
$C_1$, $C_2$ - 2 μf/6 KV
$C_3$ - 3 x 25 μf, 4KVAC (Energy storage)
$L_1$ - 11 μh (15 t. No. 12 on 2"dia. form)
VM - NEON TUBE VOLTMETER
$VA_1$, $VA_2$ - G-E V510PA80C VARISTOR
$SCR_1$ - NL C458PD (firing scr.)
$SCR_2$ - NL F397PM (commutating scr.)

Figure 10—SCR arc switch assembly (ref. fig. 1). The use of components is discussed in the text.

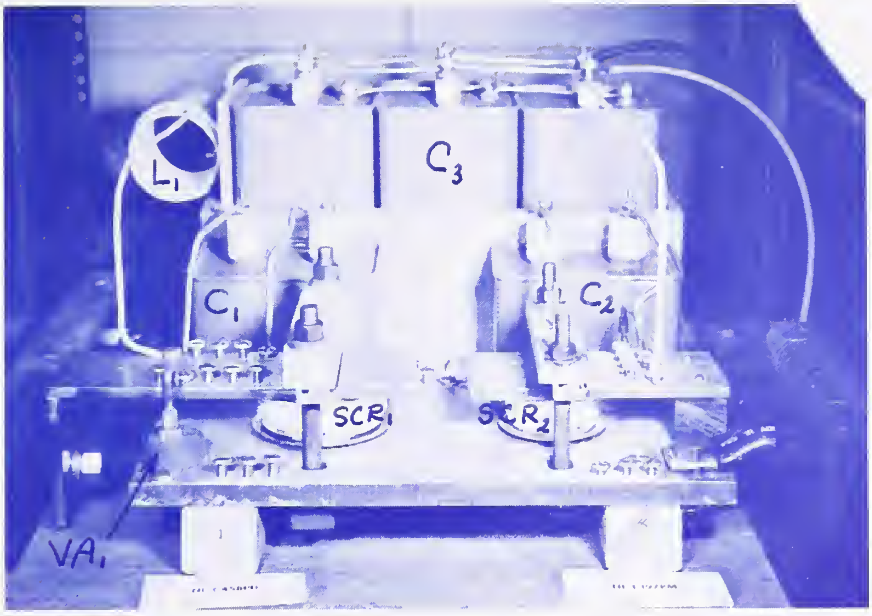
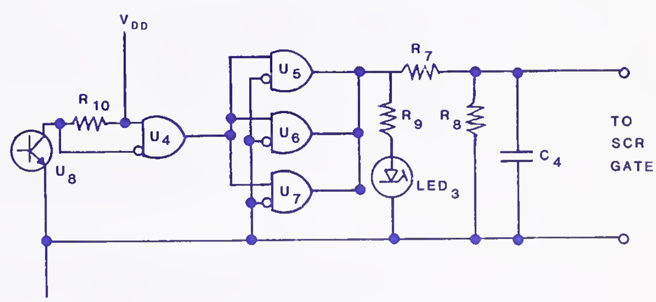



Figure 11—SCR switch assembly (ref. fig. 10). The "hockey puck" SCR's are clamped to the aluminum baseplate heatsink under approximately 1 ton of force each by the crossbars shown.

Telefunken 1981). Protection against excessive di/dt for the arc switch is provided by the inductance of the high-voltage power supply leads, which is several micro-henries; dv/dt is limited by the elements $R_5$ and $C_1$. Voltage across the device is limited by the power supply voltage, but possible spikes due to "inductive kicks" or induced voltage spikes from outside the circuit are limited by $VA_1$. Current is limited by the high-voltage power supply resistor, $R_4$. SCR's, once triggered ("fired"), must be turned off by external means. The usual method of commutation for dc circuits is to provide a current pulse in opposition to the current flow through the SCR. The pulse must be applied when the commutated SCR's gate is off, and must have sufficient energy to "hold off" the current flow long enough to meet the turn-off time specifications of the commutated SCR. Our circuit commutates the arc switch by a second SCR and an energy storage capacitor. The commutator, $SCR_2$, switches the energy stored in $C_3$ through $SCR_1$, "bucking" the arc current and turning $SCR_1$ off. The energy storage capacitor is especially constructed so as to have very low inductance. $SCR_2$ is protected against di/dt by $L_1$, which also limits the reverse di/dt of $SCR_1$. Spikes for $SCR_2$ are limited by $VA_2$, and dv/dt by $R_6$ and $C_2$.

Figure 12 is the schematic for the gate trigger circuit used for both $SCR_1$ and $SCR_2$ of figure 10. Necessary current rate-of-rise limiting is provided by $R_8$ and $C_4$, and gate current limiting by $R_7$. $LED_3$ is used for testing. The quad driver circuit shown here and in the drivers and receivers for the fiber optics (fig. 3A,B) has proven very versatile and inexpensive. The fiber optics detector used in the SCR triggers is the same as that of figure 3B.

**SCR TRIGGER CIRCUIT (TYPICAL)**




$U_4 - U_7$ - 1/4" SILICONIX D469 QUAD DRIVER
$U_8$ - G-E L14G3 PHOTOTRANSISTOR
$R_7$ - 30Ω
$R_8$ - 500Ω
$R_9$ - 1KΩ
$R_{10}$ - 5.6MΩ
$C_4$ - .003µf
$LED_3$ - 10ma RED LED

Figure 12—Schematic diagram of the SCR trigger circuit (ref. fig. 10). The switch and commutating SCR's have identical triggers.

The manual safety switch, figure 13 and on the left in figure 15, has the pneumatic interlock shown in figure 4 as the "safety bleed valve." The arc enable switch is diagrammed in figure 14 and is on the right in figure 15. These switches are, as shown in figure 10, in series with the power supply, the arc, and the arc switching SCR. Long throws are used in these safety switches to ensure that current to the arc can be interrupted if $SCR_1$ cannot be commutated. The manual switch opens to a 30-cm gap, the arc enable switch to a 20-cm gap. Large brass disks are used on these switches to give a large, low-resistance contact surface, provide a large heat capacity, and ensure that in an emergency the arc will stay between the electrodes as the switch is opened. The tube that can be seen in the manual safety switch chamber directs freon gas into the gap if necessary. It has not been used to date, although the safety aspect of the switches is proved in practice.

The commutating energy storage capacitor, $C_3$, is charged by the dc-dc converter of figures 4 and 16. This device is a "black box" that takes 12-volt dc input and gives a 400-volt dc output. The converter power is switched by the controller using $RL_1$, and the charging circuit closed by $RL_2$. $RL_2$ limits the initial charging current (theoretically infinite when the capacitor has zero charge), protecting the converter. Because the converter's internal circuitry is not known, back voltage protection is given it by $D_2$ and $D_3$.

The voltmeter detail for both the arc switch and the commutator power supply is shown in figure 17. The use of series-connected neon lamps in this circuit provides a convenient feedback through the fiber optics interface to the computer for verifying the presence of these voltages before SCR-triggering signals are given. A quick-glance visual check is also easy. A D'arsonval movement voltmeter, not shown, is also used on the commutator supply

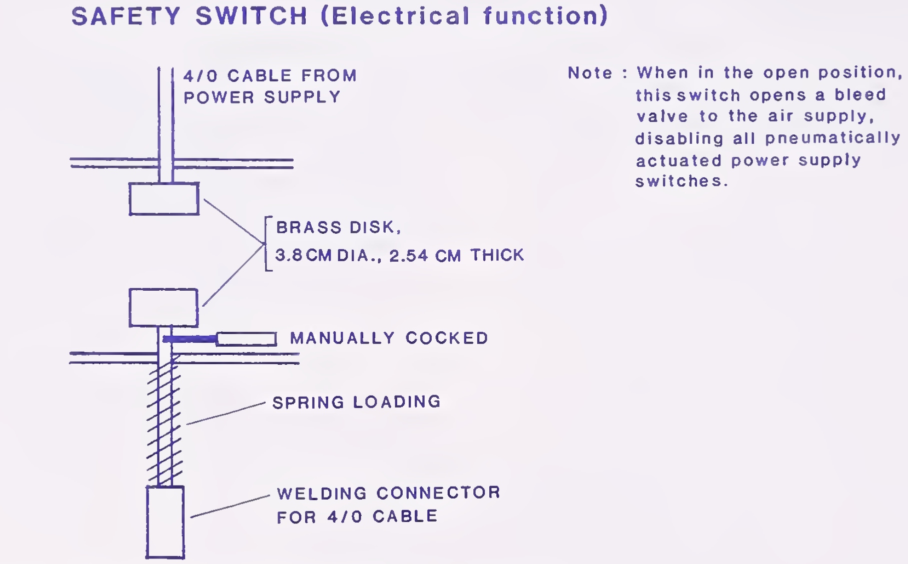



Figure 13—The manual safety switch (ref. figs. 1, 10). The long throw is necessary to interrupt the dc arc.

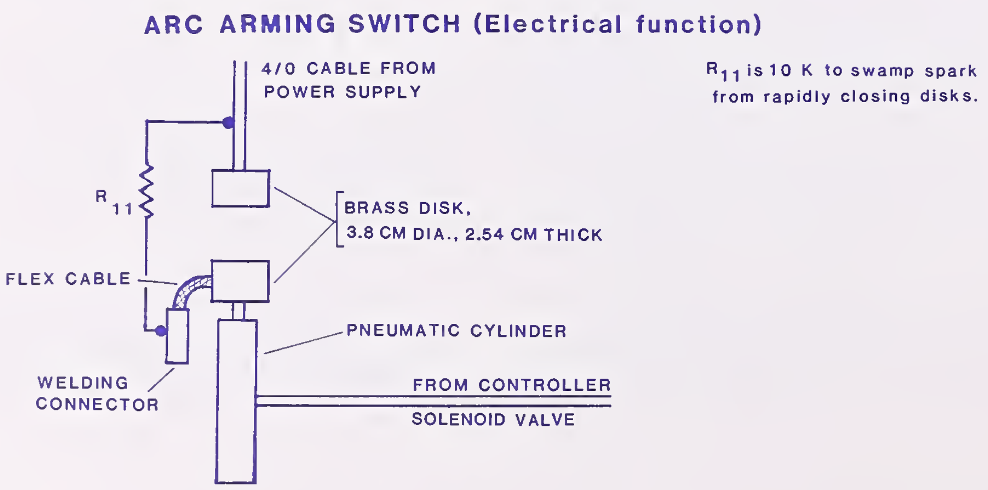



Figure 14—The pneumatic arc arming switch (ref. figs. 1, 4, 10).


Figure 15—Arc arming switch (ref. fig. 14) (right) and the manual safety switch (ref. fig. 13) (left). Note the pneumatic supply bleed valve just below the switch actuating handle. The high-voltage power supply voltmeter (ref. fig. 17) can just be seen on top of the box containing the switches.

for further visual confirmation of the commutating voltage, and to make sure visually that, after the arc cycle is finished, no charge remains on commutating capacitor $C_3$.

The arc carrier, diagrammed schematically in figure 18, is a simple arrangement for holding the copper-clad carbon arc welder cutting electrodes.

The copper cladding is removed from the rod for 5 cm or so down from the conical tip so that a minimum of copper will be involved in the arc (there is probably some small contamination). Two clamps, not shown on the diagram, hold the 4-mil tungsten wire that initiates the arc.

Fundamental measurements of the arc parameters include current in the arc circuit and voltage across the arc. Current is usually measured either by measuring the voltage drop across a resistance or, for pulses, by a transformer. Although elaborate precautions are not usually necessary for measuring the moderately high voltages used in the arc generator, the unusually low source impedance (current-source capacity) of the battery supply calls

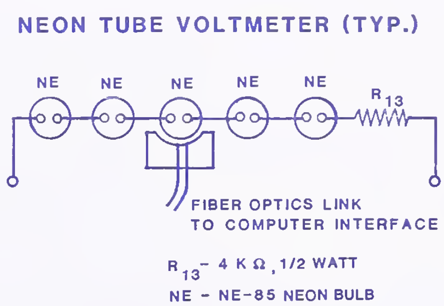



Figure 17—Neon tube voltmeter. The arc circuit (ref. figs. 10, 15) and the commutator power supply (ref. fig. 16) include one of these devices.

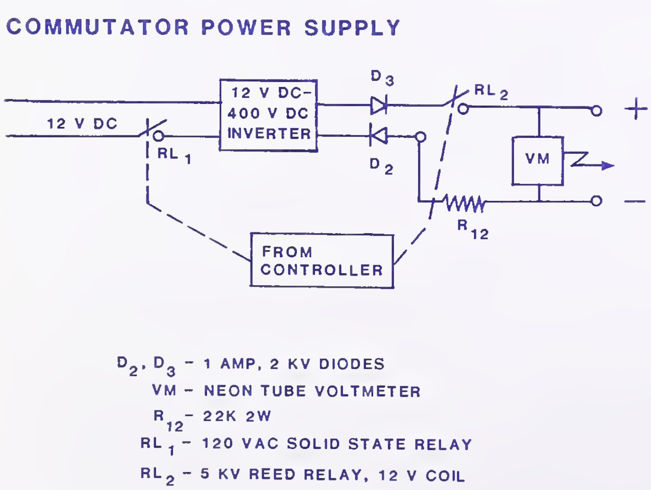



Figure 16—Commutator capacitor charging power supply (ref. fig. 4).

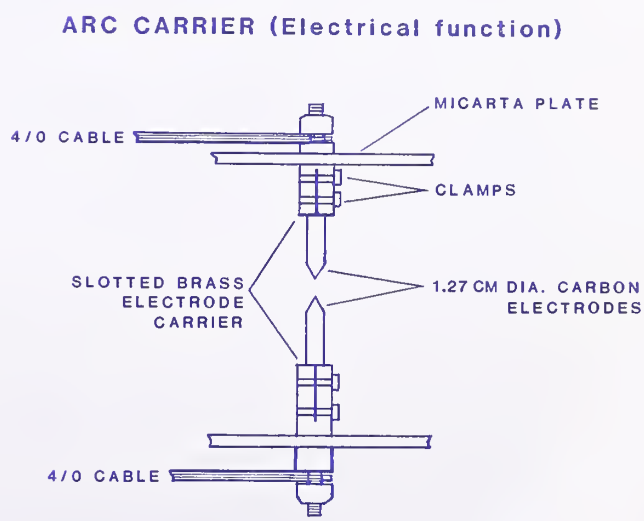



Figure 18—Arc generator electrode construction (ref. fig. 10).

for more than usual care with respect to grounding and measurement procedures. Large current flows result in large voltage drops across what can usually be considered negligible resistances. To avoid potentially dangerous ground loops, we have gone to great pains to isolate the high-current circuit from ground. To make current measurements with grounded apparatus would defeat this end.

Fortunately, the high currents give us a solution to this problem. A current flow generates a magnetic field which, if measured with attention to the geometry of the measurement, allows calculation of the current causing it. We found an inexpensive Hall-effect device for measurement of magnetic fields. A test verified that the rise time of the device and its associated circuitry (fig. 19A,B) was at least an order of magnitude better than the turn-on time of the switch.

We had an isolation amplifier on hand for voltage measurement. This amplifier had a rise time that was too slow to be used in a current measurement, although we might have done so. It could, however, be used in calibration and, in use of the generator, phenomena with tens-of-milliseconds and longer timescales. A simple resistor voltage divider was constructed to accommodate the voltage range of arc operation, and the assembly calibrated with a power supply and digital voltmeter. The voltage-measuring circuit is not diagrammed because it is straightforward. The luminosity measurement is done with a simple solid-state photovoltaic photodiode (EG&G SD-100).

The series resistor was accurately measured with a Wheatstone bridge, and the current device calibrated using the arc generator with the arc gap shorted. Measurement precision is 1 percent or better depending on the readout device for the current and voltage circuits. Accuracy depends on the readout device as well. We are not asking for better than 2 to 3 percent accuracy in the experimental design, and will be doing well to get that with the variables associated with real fuels in the ignition testing.

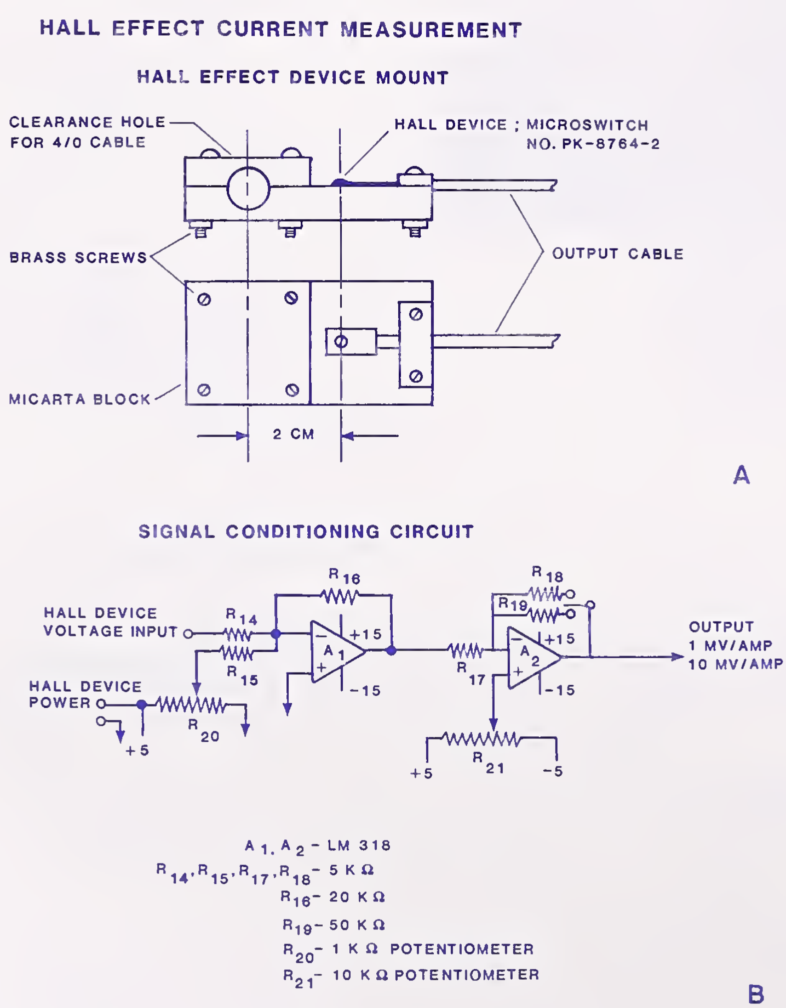



Figure 19—Hall-effect current measurement device (ref. fig. 1). The use of the device is apparent from part A of the figure. The Hall device is held at a known distance from the center of the cable and measures the magnetic field generated by the current flow.

## OPERATION

The operation of the arc generator is under computer control. The sequence of steps is as follows:

1. The program is started.
2. The program prompts the operator to put a wire in the arc gap.
3. The program prompts the operator to close the manual safety switch.
4. The operator is prompted to turn on the main air supply switch.This turns on the controller power supply.
5. The operator is asked for the desired arc duration (> 20 ms, < 1 sec).
6. The program now assumes control of the operation.
7. The commutator power supply is energized.
8. The commutator charging switch is closed.
9. When the commutator is charged, the high-voltage switches are closed; otherwise abort.
10. When the high-voltage switches are closed, the arc enable switch is closed; otherwise abort.
11. The program waits for a manual firing command; otherwise aborts after 30 seconds.
12. The commutator charging and power supply switches are opened.
13. The arc SCR is triggered.
14. After the requested delay (step 5), the commutating SCR is triggered.
15. All switches are opened.
16. After a 2-sec delay, the commutator charging switch is closed (to fully discharge the commutating capacitor).
17. Success is announced, and the operator asked to turn off the air supply and open the manual safety switch.
18. The program returns to step 1 for the next shot.
19. If an abort has occurred, the commutator capacitor is discharged, and an abort is announced.
20. The program returns to start.

The program for carrying out this procedure is listed in the appendix.

## PERFORMANCE

Typical results ot operation of the arc generator are shown in figures 20 and 21. The upper trace of figure 20 is a current measurement with a 1.21-ohm series resistor and a shorted gap. There is a very gradual increase in the current with time due to heating of the resistor. In this example, the resistor was dissipating 96 kw and the total energy loss in the resistor was 3,368 Joules. The spike on the stopping transient is caused by the dumping of charge by the commutating capacitor, $C_3$. Figure 21 shows the result of recording the current flow and voltage across a typical arc of 6 cm length. This record, as well as the previous one, demonstrates the poor response of the isolation amplifier

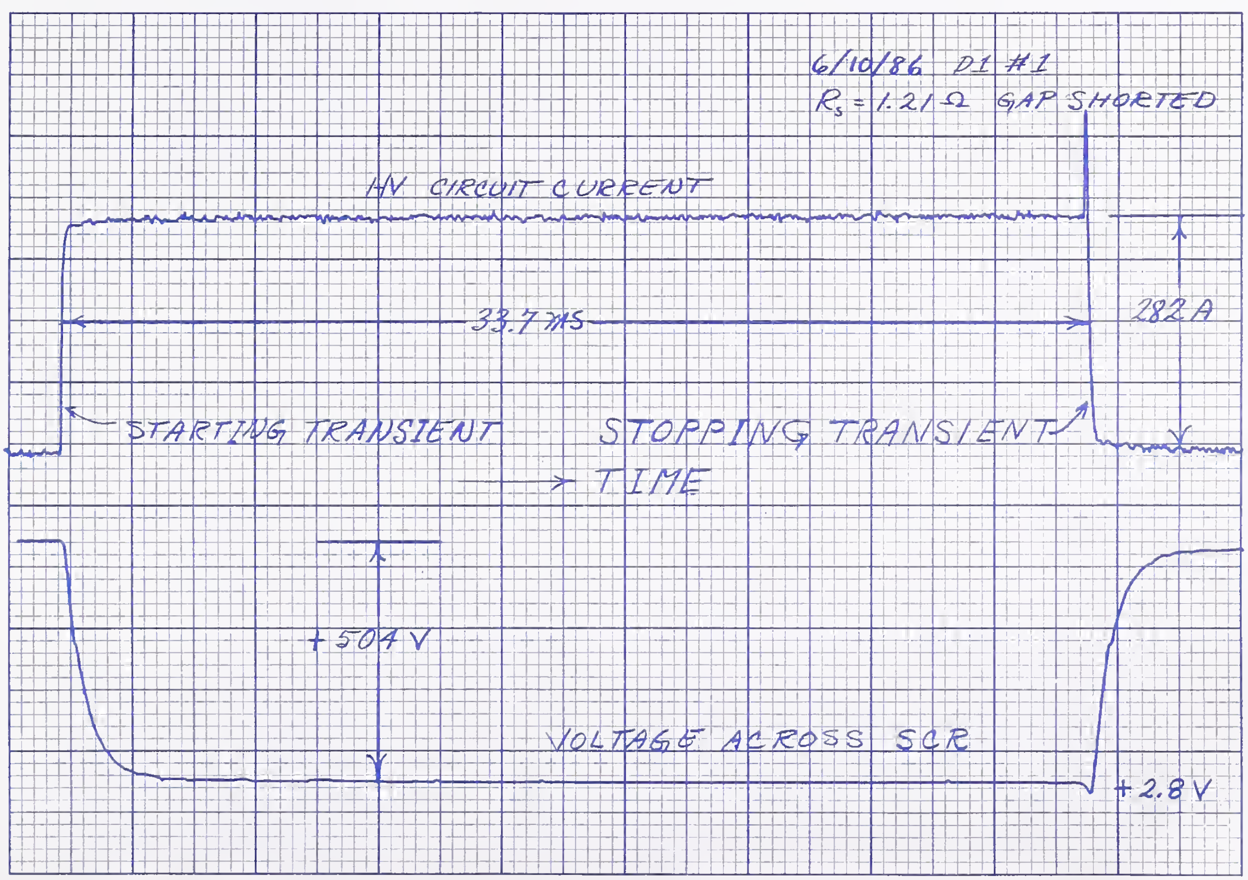



Figure 20—Current in the arc circuit and voltage across $SCR_1$ (ref.fig. 10) for a nominal 35 ms duration pulse. The arc gap was shorted with battery jumper cables for this test.

used for voltage measurement. The initial current pulse and subsequent fall in current are due to the tungsten wire heating and burning through. Copious electrons are provided by this mechanism, and, when the wire burns through, the arc strikes in the ionized channel left by the wire. The arc grows in diameter (according to our models), with a consequent increase in current flow, until an apparent equilibrium is reached. The power in the arc is about 24 kw, and the energy dissipation about 1,000 Joules. We are presently investigating the electrical characteristics of the arc and the details of arc striking.

Altogether, we are pleased with the performance of the arc generator. It meets the design criteria, especially those generated by safety considerations. With only two exceptions, the switching and control circuits have performed well. The cause of the exceptions has been corrected. The only nagging problem with the system is periodic cleaning of the power supply switches. Because we will be finished with the experiment in the near future, we will not plate the electrodes, which would solve this problem.

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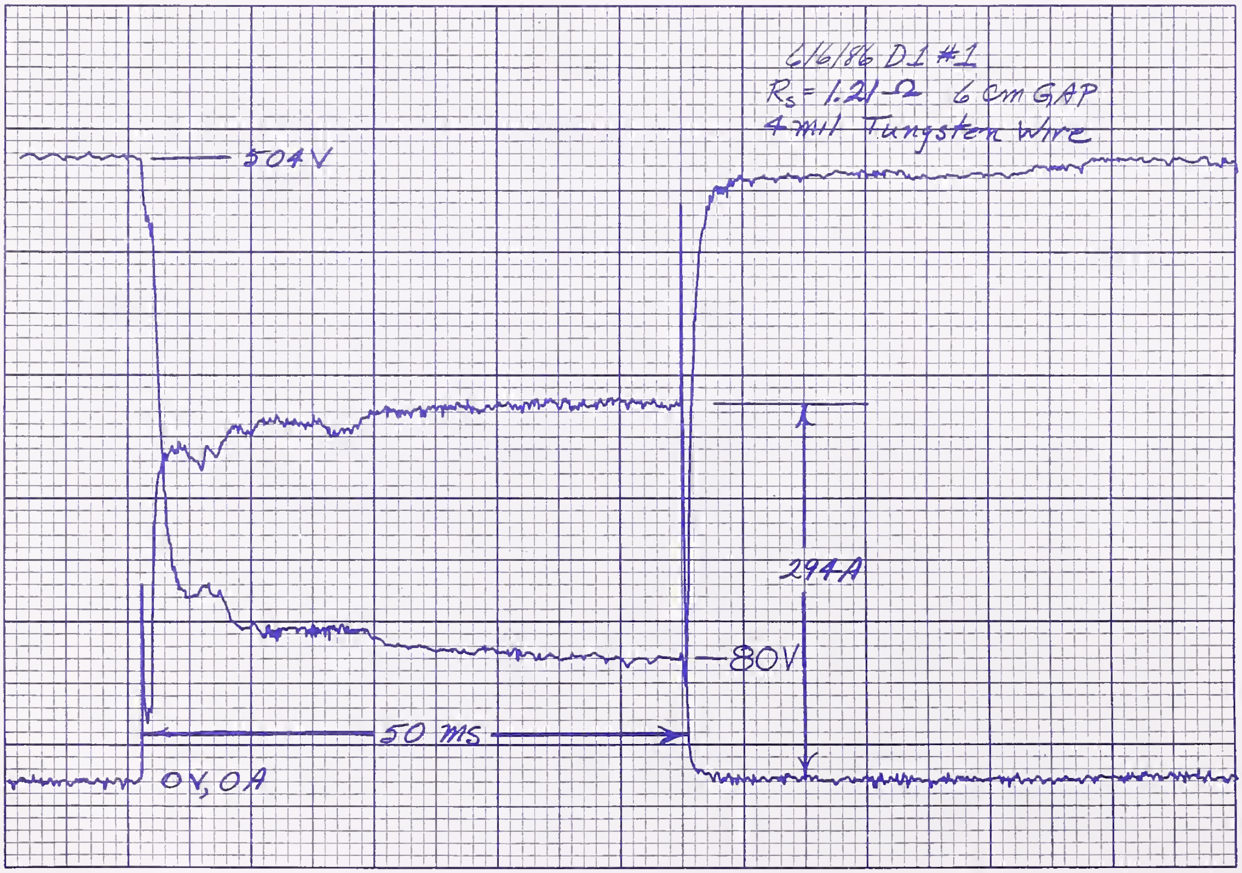


Figure 21—Current in the arc circuit and voltage across the arc gap (ref. fig. 10) for a nominal 50 ms duration pulse.

## APPENDIX: OPERATING SEQUENCE OF ARC GENERATOR

```
READY.

 100 REM THE ALL-NEW FIRING PROGRAM
 120 REM READ INPUTS AT 1000
 140 REM SEND OUTPUTS AT 2000
 160 REM DELAY AT 3000
 200 REM MSD "1" IS ARC SCR TRIGGER
 210 REM MSD "2" IS COMMUTATOR TRIGGER
 220 REM 2SD "1" IS COMMUTATOR CHARGE SW
 230 REM 3SD "1" IS ARC ARMING SWITCH
 240 REM 3SD "2" IS HV BATTERY SWITCHES
 250 REM 4SD "1" IS COMMUTATOR PS SWITCH
 260 REM INPUTS ARE AS FOLLOWS:
 270 REM MSD"1"IS COMMUTATOR CHARGED,CC$ 280 REM 2SD"1"IS HV SUPPLY ON, HV$
 290 REM 3SD"1"IS LV AND AIR ON, LV$
 300 REM 4SD"1"IS FIRE BUTTON ON, FA$
 310 REM ALL THESE ARE ON IEEE DEVICE 5
 320 REM NICOLET SCOPE IS DEVICE 15
 330 REM OPEN AND INITIALIZE ALL
 350 CR$=CHR$(13)
 360 OF$="0000"+CR$
 370 T1$="1"+CR$+"0"+CR$:REM FIRING PULSE
 380 T2$="2"+CR$+"0"+CR$:REM COMMUTATOR PULSE
 390 Z$="0"
 400 OPEN 5,5:OPEN15,15
 420 MS$=OF$:GOSUB2000
 500 REM HERE WE GO
 520 PRINT"   PUT A WIRE IN THE GAP AND"
 540 PRINT"CLOSE THE SAFETY SWITCH."
 560 PRINT"THEN TURN ON THE MASTER AIR SUPPLY"
 580 GOSUB 4000
 600 TR=0:GOSUB3000
 610 GOSUB 1000
 620 GOSUB 3000
 630 IF TU=1 THEN GOTO 50000
 640 IF LV$<>"1" THEN 610
 650 PRINT"AIR SUPPLY AND LOW VOLTAGE  ON "
 670 GOSUB 5000
 690 PRINT"*** CHARGING COMMUTATOR ***"
 700 MS$="0001":GOSUB2000
 800 TR=0
 810 MS$="0101":GOSUB2000
 820 GOSUB1000:GOSUB3000
 830 IF TU=0 AND CC$="0" THEN 820
 840 IF TU=1 THEN 50000
 850 IF CC$="1" THENPRINT"  COMMUTATOR CHARGED "
 870 MS$="0121":GOSUB2000:TR=0
 880 GOSUB1000:GOSUB3000
 885 IF HV$="0" AND TU=0 THEN 880
 890 IF TU=1 THEN 50000
 900 IF HV$="1" THENPRINT:PRINT"     HIGH VOLTAGE READY"
 902 MS$="0131":GOSUB2000
 905 FOR FR=1TO3000:NEXTFR
 907 SC$="H0":GOSUB2200
 908 TR=0
 910 PRINT"    PRESS FIRE BUTTON TO FIRE     "
 920 GOSUB1000:GOSUB3000
```

```
930 IF FA$="0" AND TU=0 THEN 910
940 IF TU=1 THEN 50000
950 IF FA$="1" THEN GOSUB 30000
960 GOTO 40000
999 END
1000 REM READ INPUTS
1020 CC$=Z$
1040 LV$=Z$
1060 HV$=Z$
1080 FA$=Z$
1200 INPUT#5,I$
1220 CC$=MID$(I$,1,1)
1240 HV$=MID$(I$,2,1)
1260 LV$=MID$(I$,3,1)
1280 FA$=MID$(I$,4,1)
1999 RETURN
2000 REM SEND MS$ TO COUPLER
2020 PRINT#5,MS$
2040 MS$=""
2099 RETURN
2200 REM SEND TO NICOLET
2220 PRINT#15,SC$
2230 SC$=""
2999 RETURN
3000 REM TIME DELAY
3020 TU=0
3040 IF TR=0 THEN TI$="000000"
3050 IF TI$<"000030" THEN TR=1:RETURN
3060 TU=1
3070 TR=0
3999 RETURN
4000 REM GET A SINGLE KEY AND INTERPRET
4010 KY$=""
4020 PRINT:PRINT"    G TO CONTINUE, SPACE TO STOP    ":PRINT
4040 GET KY$:IF KY$=""THEN4040
4060 IF KY$="G" THEN RETURN
4080 IF KY$=" "THEN 50000
4100 GOTO 4040
4999 REM END OF KEYIN
5000 REM CALCULATE DELAY NUMBER
5020 PRINT:INPUT"  DELAY IN MS";DE
5040 DE=INT((DE-19.35)/1.079)
5060 IF DE<0 THENPRINT" DELAY TOO SHORT":GOTO 5020
5999 RETURN
30000 REM TURN OFF COMMUTATOR AND FIRE
30020 REM DE IS THE DELAY NUMBER
30040 MS$="0030":GOSUB2000
30060 FOR DD=1 TO 10:NEXT
30080 PRINT#5,T1$;
30100 FOR DL=1TODE:NEXT
30120 PRINT#5,T2$;
30140 RETURN
40000 REM SUCCESSFUL OPERATION
40020 MS$=OF$
40030 GOSUB 2000
40040 PRINT"   SUCCESSFUL SHOT   "
40045 GOSUB51000
```

## APPENDIX (Con.)

```
 40050 GOSUB 4000
 40060 RUN
 50000 REM UNCONDITIONAL QUIT
 50100 PRINT"        OPERATION ABORTED        "
 50110 GOSUB1000
 50120 IF TU=1 THEN PRINT "    DUE TO TIMEOUT"
 50140 IF CC$=Z$ THEN PRINT"    COMMUTATOR NOT CHARGED"
 50160 IF LV$=Z$ THEN PRINT"    AIR OR LOW VOLTAGE NOT ON"
 50180 IF HV$=Z$ THEN PRINT"    HIGH VOLTAGE NOT ON"
 50200 MS$=OF$
 50220 GOSUB 2000
 50240 GOSUB 51000
 50300 CLOSE 5:CLOSE 15
 50999 END
 51000 REM BLEED COMMUTATE CAPACITORS
 51020 REM ALLOW HVPS SWITCHES TO OPEN
 51040 FOR KL=1TO3000:NEXT
 51050 PRINT:PRINT"    BLEEDING COMMUTATOR ":PRINT
 51060 MS$="0100"
 51080 GOSUB2000
 51100 TR=0
 51120 GOSUB 3000
 51140 IF TU=0 THEN 51120
 51145 TU=0
 51160 MS$=OF$
 51180 GOSUB 2000
 51200 RETURN
 59999 END
READY.
```

## INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

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June 1987
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